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Effect of the density of collision cascades on implantation damage in GaN

S. O. Kucheyev[a] and J. S. Williams
Department of Electronic Materials Engineering, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT 0200, Australia

A. I. Titov
Department of Physical Electronics, St. Petersburg State Technical University, St. Petersburg 195251, Russian Federation

G. Li
Ledex Corporation, No. 9, Ta-Yio First St., Ta-Fa Industrial District, Kaohsiung County, Taiwan, Republic of China

C. Jagadish
Department of Electronic Materials Engineering, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT 0200, Australia

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Damage accumulation in wurtzite GaN films bombarded with 0.5 MeV Bi_1 and 1 MeV Bi_2 ions (the so-called molecular effect) is studied by Rutherford backscattering/channeling spectrometry. Results show that an increase in the density of collision cascades dramatically enhances the level of implantation-produced lattice disorder in GaN. This effect is attributed to (i) an increase in the defect clustering efficiency with increasing density of ion-beam-generated point defects and/or (ii) to collective nonlinear energy spike processes. Such a strong influence of the density of collision cascades is important to take into account for a correct estimation of implantation-produced lattice disorder in GaN. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1369149]

Ion implantation is a very attractive technological tool for selective-area doping of GaN, a material of significant technological importance.[1] However, at this stage, a successful selective-area doping of GaN by ion implantation (particularly in the case of high ion doses needed for *p*-type doping and Ohmic contact applications) is often hindered by ion-beam-produced lattice disorder and its undesirable consequences. A number of rather complex ion-beam-damage processes in GaN (such as extremely strong dynamic annealing, somewhat unexpected defect evolution, and ion-beam-induced material dissociation and anomalous surface erosion) have been revealed in our recent studies.[2–8] Because GaN exhibits such an extreme behavior and somewhat unexpected property changes under ion bombardment, it is important to undertake systematic studies of ion-beam-damage processes in this material if potential applications are to be fully exploited.

In this letter, we study the molecular effect in damage accumulation to ascertain the influence of the density of collision cascades on ion-beam-produced lattice disorder in GaN. Such a molecular effect is studied by comparing levels of lattice disorder produced by bombardment with atomic and molecular ions of equal velocity.[9] Our results reveal that the molecular effect in GaN is extremely large, which reflects the important role of the density of collision cascades in the damage buildup in this material. In comparison, the molecular effect in Si, as expected, is much weaker.

The ~ 2-μm-thick wurtzite undoped GaN epilayers used in this study were grown on *c*-plane sapphire substrates by metalorganic chemical vapor deposition (MOCVD) in a rotating disk reactor at Ledex Corporation. Implantation with 0.5 MeV $^{209}Bi_1^+$ and 1 MeV $^{209}Bi_2^+$ ions was done at -196 and 20 °C with a beam flux of $\sim 1\times 10^{11}$ Bi atoms/(cm^2 s) over the dose range from 2×10^{12} to 6×10^{14} Bi atoms/cm^2 using an ANU 1.7 MV tandem accelerator (NEC, 5SDH-4). During implantation, samples were tilted by $\sim 7°$ relative to the incident ion beam to minimize channeling.

After implantation, samples were characterized *ex situ* by Rutherford backscattering/channeling (RBS/C) spectrometry using an ANU 1.7 MV tandem accelerator (NEC, 5SDH) with 1.8 MeV $^4He^+$ ions incident along the [0001] direction and backscattered into a detector at 98° relative to the incident beam direction. This glancing-angle detector geometry was used to provide enhanced depth resolution for examining near-surface damage accumulation.

Figures 1 and 2 show selected RBS/C spectra that illustrate the damage buildup with increasing dose of 0.5 MeV Bi_1 and 1 MeV Bi_2 ions at 20 (Fig. 1) and -196 °C (Fig. 2). For implantation with atomic species (Bi_1), Figs. 1 and 2 show a damage buildup behavior which is expected for the heavy-ion bombardment regime, as has been studied in detail in Ref. 4 in the case of implantation with keV ^{197}Au ions. Indeed, at room temperature (see Fig. 1), with increasing dose of heavy atomic ions, damage accumulation is bimodal with preferential surface disordering and amorphization proceeding layer-by-layer from the surface, while the disorder level in the bulk saturates after some ion dose. In contrast, liquid-nitrogen-temperature bombardment with heavy atomic

[a]Electronic mail: sergei.kucheyev@anu.edu.au

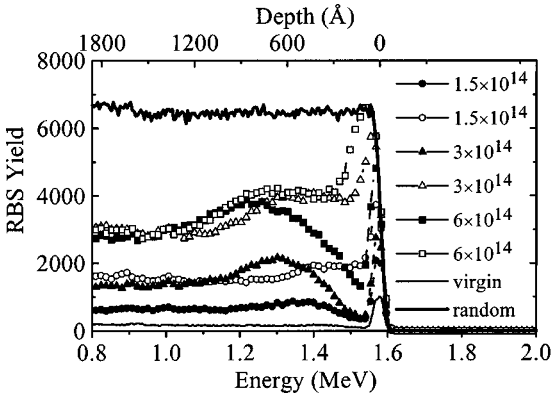

FIG. 1. RBS/C spectra showing the damage buildup for 0.5 MeV Bi_1 (closed symbols) and 1 MeV Bi_2 (open symbols) ion bombardment of GaN at 20 °C with a beam flux of $\sim 1\times 10^{11}$ Bi atoms/(cm^2 s). Implantation doses (in Bi atoms/cm^2) are indicated in the figure.

ions (see Fig. 2) results in bulk amorphization in addition to layer-by-layer amorphization proceeding from the surface.[4]

What is more interesting from Figs. 1 and 2 is that bombardment with molecular ions (Bi_2) results in significantly larger levels of lattice disorder (particularly in the near-surface region) than irradiation with atomic ions (Bi_1) of the same velocity. To illustrate how unexpectedly large the molecular effect in GaN is, the inset in Fig. 2 shows typical RBS/C spectra illustrating the molecular effect in Si bombarded with the same 0.5 MeV Bi_1 and 1 MeV Bi_2 ions at -196 °C to a dose of 8×10^{12} Bi atoms/cm^2. It is seen from this inset that, in the case of Si, the molecular effect is significantly weaker than for GaN, and the level of lattice disorder produced by atomic or molecular ions differs only in the near-surface region.

Another interesting feature seen from Fig. 2 is that, in the case of implantation of GaN at -196 °C, irradiation with molecular ions apparently changes the damage buildup mode. In the case of atomic Bi_1, the disorder profile is bimodal with amorphization in the crystal bulk, while for molecular Bi_2, preferential disordering of the near-surface region dominates. Indeed, Fig. 2 shows that, during heavy atomic ion bombardment at -196 °C, lattice disorder accumulates at the GaN surface (resulting in a surface amorphous layer, as discussed in Ref. 4) and in the bulk (in the region of the maximum of the nuclear energy-loss profile of heavy ions). The region between the surface amorphous layer and the bulk defect peak is nearly defect free (see Fig. 2), presumably due to defect annihilation as well as migration of point defects from this region towards the surface. Figure 2 also shows that, in contrast to the case of implantation with atomic Bi_1 ions, this region between bulk and surface peaks of disorder is highly disordered (but not amorphous) by Bi_2-ion bombardment at liquid-nitrogen temperature. A similar preferential disordering of the (near-surface) region between the surface amorphous layer and the bulk defect peak is seen in Fig. 1 in the case of Bi_2-ion implantation at room temperature as compared to Bi_1-ion irradiation. As discussed more fully below, such preferential disordering of the near-surface region (at the beginning of ion trajectories) is an intrinsic feature of the molecular effect.

The nature of the molecular effect in Si under heavy-ion bombardment is generally explained within the framework of the nonlinear energy spike concept (such as displacement and/or thermal spikes).[9] Indeed, a spatial overlap of collision cascades produced by atoms which form a molecular ion (and, hence, simultaneously impact the target surface) results in an increase in the density of collision cascades. This effect is particularly pronounced in the near-surface region, at the beginning of ion trajectories, before the ions forming a molecular ion are scattered to large distances compared with the lateral size of collision cascades. Based on the energy spike concept,[9] resultant lattice disorder (in the form of completely disordered or amorphous zones) superlinearly depends on the density of the energy lost by heavy ions in the nuclear energy-loss processes. Such nonlinearity is usually invoked to account for the molecular effect in Si under heavy-ion bombardment.[9]

These nonlinear energy spike processes (which are well accepted in the literature in the case of Si) may contribute to the large molecular effect observed in GaN (see Figs. 1 and 2). Indeed, based on the energy spike concept,[9] the formation of a completely disordered or amorphous zone in a dense collision cascade occurs within a very short time interval (~ 10 ps). However, amorphous zones are not observed in GaN during *ex situ* transmission electron microscopy studies reported in Ref. 4 and appear to be unstable. Immediately after the quenching of collision cascades, highly disordered regions may incompletely recrystallize, leaving point defects and defect clusters in the lattice even at liquid-nitrogen temperature. This is somewhat similar to the situation known for most metals during ion irradiation.[10] Hence, even at -196 °C in GaN, the damage buildup is dominated by point defects and defect complexes which survive the fast quenching of collision cascades.[4] The strong molecular effect, therefore, can be attributed to an increase in the defect clustering efficiency with increasing density of collision cascades in the case of implantation with molecular ions as compared to the case of atomic ion bombardment.[11] Such an explanation is supported by the strong flux effect observed in GaN bombarded with heavy ions (^{197}Au) at 20 and -196 °C.[4] Indeed, increasing defect generation rate at high ion fluxes en-

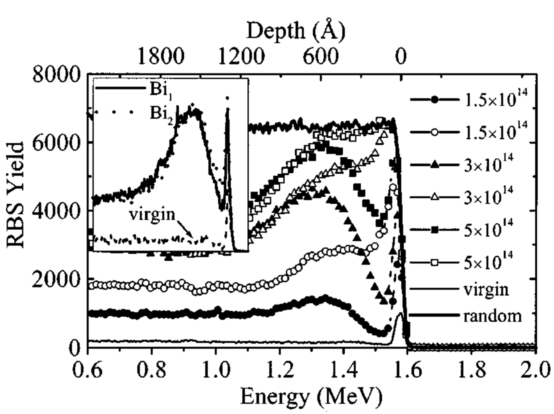

FIG. 2. RBS/C spectra showing the damage buildup for 0.5 MeV Bi_1 (closed symbols) and 1 MeV Bi_2 (open symbols) ion bombardment of GaN at -196 °C with a beam flux of $\sim 1\times 10^{11}$ Bi atoms/(cm^2 s). Implantation doses (in Bi atoms/cm^2) are indicated in the figure. For comparison, the inset illustrates RBS/C spectra of Si bombarded with 0.5 MeV Bi_1 and 1 MeV Bi_2 ions at -196 °C to a dose of 8×10^{12} Bi atoms/cm^2.

hances interactions between mobile point defects, which aids the formation of stable defect complexes.

It should be noted that there are also other processes which may contribute to the strong molecular effect observed in GaN in this study. For example, the effective displacement energy of atoms in the GaN matrix may decrease with increasing density of collision cascades. Such a decrease in the effective displacement energy may result from either the breaking of a large number of atomic bonds within a relatively small volume of a collision cascade or the reduced displacement energy of atoms with missing nearest neighbors which arises due to a very high displacement density.[9] There may be also local material decomposition occurring within dense collision cascades, as has been discussed in more detail previously.[4,6] Both of these effects would also be expected to result in a superlinear dependence of ion-beam-generated defects on the density of collision cascades.

In conclusion, the molecular effect in damage buildup in wurtzite GaN has been studied in the case of heavy-ion ($^{209}Bi_1$ and $^{209}Bi_2$) bombardment. Results reveal an unexpectedly strong dependence of implantation-produced lattice damage on the density of collision cascades. This interesting effect has been attributed to a combination of (i) an increase in the defect clustering efficiency with increasing local density of ion-beam-generated mobile point defects and/or (ii) collective energy spike processes resulting from the overlap of collision cascades. In the latter case, increased disorder results from a superlinear dependence of the concentration of ion-beam-produced point defects, which survive cascade quenching, on the density of collision cascades. Awareness of such a large influence of the density of collision cascades on implantation-produced disorder is required for a correct estimation of implantation damage in GaN.

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[9] For a detailed discussion of the molecular effect, see, for example, J. A. Davies, in *Ion Implantation and Beam Processing*, edited by J. S. Williams and J. M. Poate (Academic, Sydney, Australia, 1984), p. 81; A. I. Titov and S. O. Kucheyev, Nucl. Instrum. Methods Phys. Res. B **149**, 129 (1999), and references therein.
[10] See, for example, J. S. Williams, Rep. Prog. Phys. **49**, 491 (1986).
[11] A similar scenario may be proposed to explain the molecular effect previously observed in the case of *light-ion* bombardment of Si, where the molecular effect is usually attributed to nonlinear energy spike processes resulting from a spatial overlap of (relatively dense) collision subcascades. However, an increase in the defect clustering efficiency with increasing the local density of ion-beam-generated point defects seems to be an alternative explanation for the molecular effect in the case of light-ion bombardment of Si.